Frequency Stable Fiber Lasers for Optical Remote Sensing

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NKT Photonics A/S

Denmark

NKT Photonics

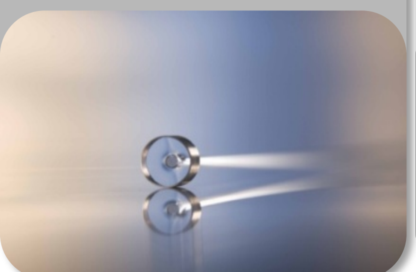
Crystal Fibre | **aeroGAIN** | **Koheras** | **SuperK** | **Argos**

High Peak Power Pulsed Lasers
- Material Processing
- Military & Defense
- High-end research & development
- Gyroscope

Advanced sensing
- Wind LIDAR
- Seismic
- Security
- SHM

Replacement of conv. multiple lasers
- Imaging (bio.)
- Inspection (semicon.)
- High-end R&D

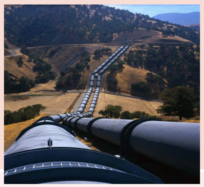
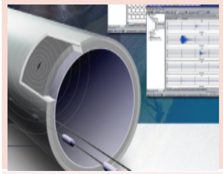
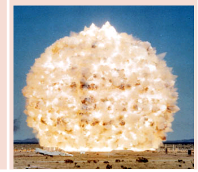
Spectroscopy
- Military & Defense
- High-end research & development



Outline

- Laser source requirements for remote sensing
- Compact, low noise lasers
- Fiber DFB laser:
  - general operational principles
  - noise
  - frequency stability
  - multi channel sources
  - high power systems
- Applications
- Summary

Laser based remote sensing

Security	Seismic	Structural Health Monitoring	Vibrometry	Wind LIDAR / Ranging	PDV
					
Pipes Fences Data	Oil &Gas exploitation Navy	Water pipes Oil and gas pipes Other	Laser Doppler vibrometry	Wind turbines Wind assessment Airports Atmospheric sensing Aircraft monitoring	Shock wave analysis @ km/sec velocities

... extensive use of coherent detection principles to overcome limitations of weak return signals

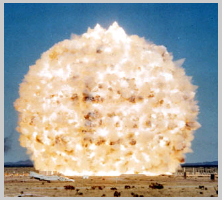
Laser source requirements for remote sensing applications

Fiber optic sensing: low levels of change in phase, frequency or intensity ⇒

- low noise laser source – low phase & amplitude noise
- compact
- fiber coupled
- maintenance free
- some applications: frequency tuneability
- some applications: high power

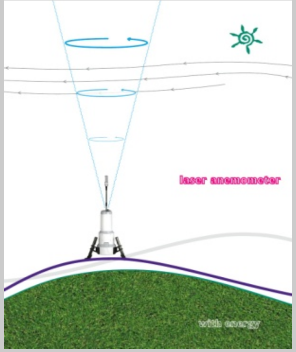
PDV specific requirements:

- high degree of frequency stability
- multi-channel systems
- high power (Watt level)



Example: Wind LIDAR

- back scatter coefficient from atmospheric aerosols <10^{-14} (depending on aerosol concentration)
- => good signal-to-noise ratio: low laser noise & high power



Compact low noise laser sources

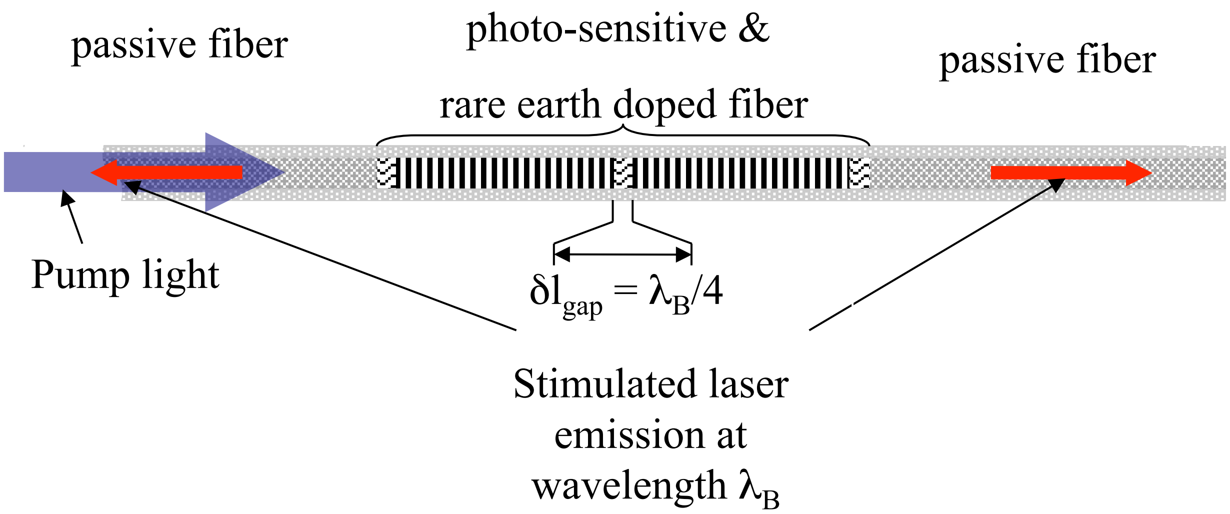
NPRO laser set the standard for compact low noise lasers for years.

Last 10 – 15 years: **new class of laser products** for fiber optic and remote sensing.

- greater wavelength selection
- compact (similar foot print)
- fiber coupled
- maintenance free
- single frequency
- narrow linewidth
- low phase noise – comparable to NPRO

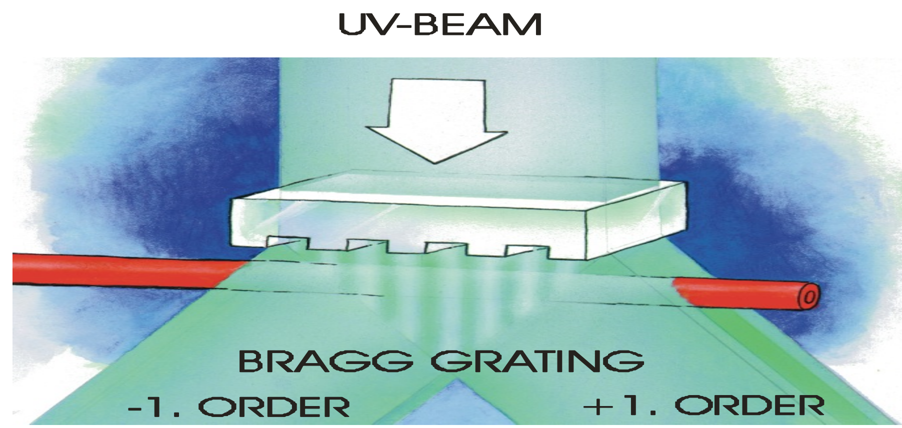
NKT Photonics's **Koheras BASIK module** fiber laser is an example of a new class compact, low noise laser source

Focus: Distributed Feed-Back Fiber Laser – UV processing



Typical length:

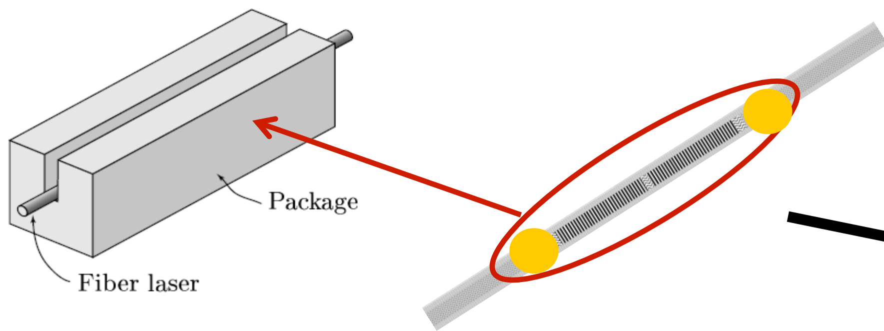
few cm

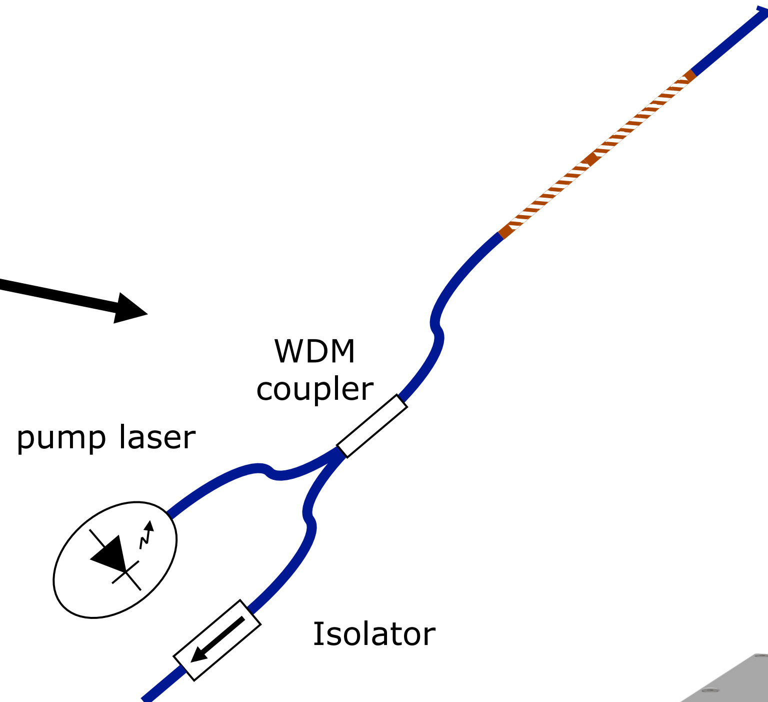


Laser wavelength:

$$\lambda_B = \Lambda_B \cdot n(\lambda_B, \varepsilon, T)$$

Distributed Feed-back fiber laser - packaging





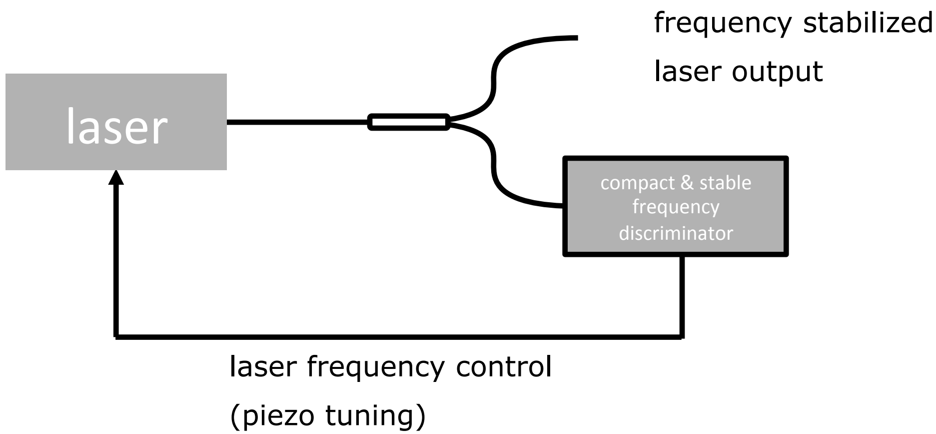
Fiber laser grating mounted under tension on substrate.

$\lambda_B = \Lambda_B(\varepsilon,T) \cdot n(\lambda_B,\varepsilon,T)$

Fiber laser **wavelength** determined by grating pitch, tension, temperature

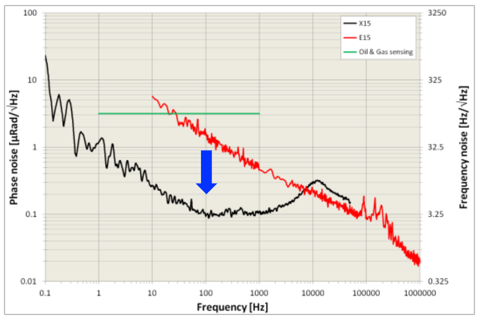
X15 - a new class of frequency stabilized fiber lasers with lower phase noise & higher frequency stability

Frequency-lock fiber laser to compact & stable frequency reference:



- reduce phase noise
- Meet requirements for Geo-seismic fiber optic sensing: low phase noise @ low frequencies

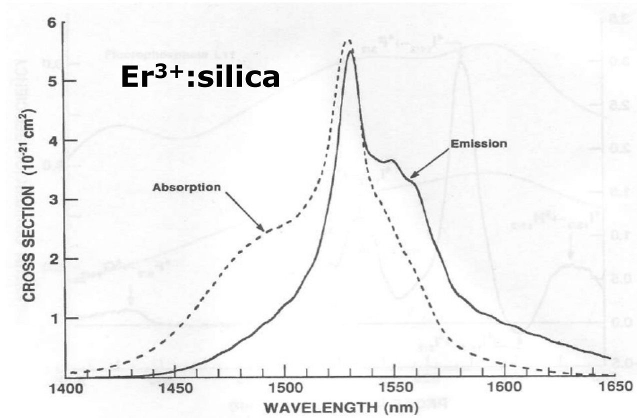
Frequency stabilized fiber DFB laser module (X15)

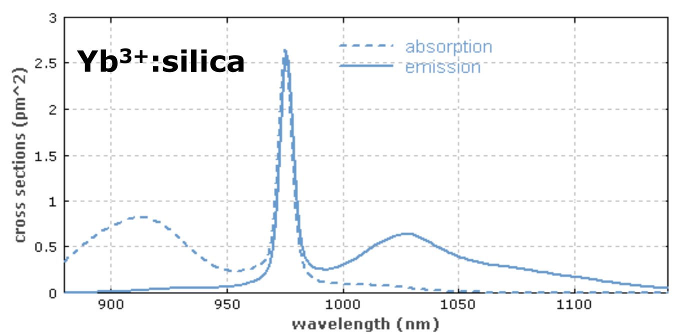


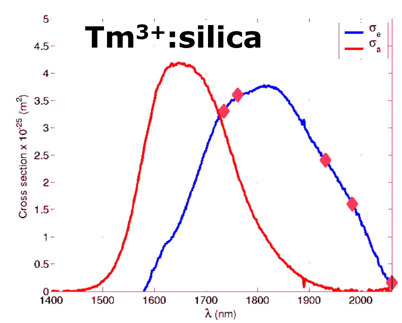
Wavelength ranges

DFB fiber lasers wavelength ranges given by rare-earth spectra

RE dopant	Wavelength range
Yb	980-1200 nm
Er	1500-1620 nm
Tm	1730-2100 nm





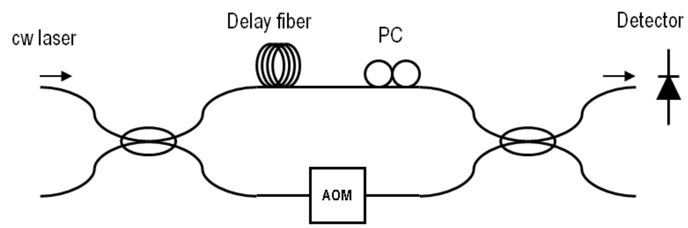


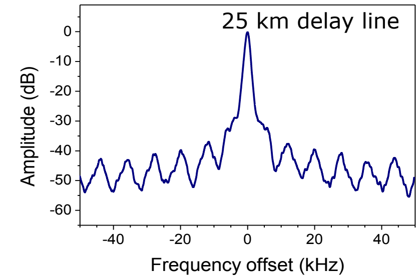
Spectral linewidth

Spectral linewidth:

Measure of the spectral content of the laser signal. Self-heterodyne beat method with 25 km fiber delay = 120µsec. Typical linewidth value of 1 kHz.

self-heterodyne beat method:

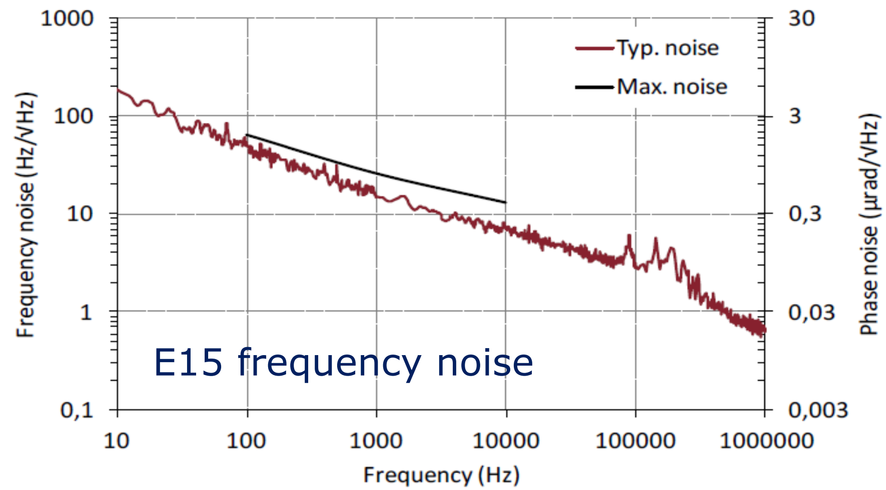




Fiber lasers: dominated by 1/f flicker noise => measured **Gaussian linewidth** represents a measure for the **frequency jitter of a much narrower line over the integration time of the measurement.**

An upper limit on the **Lorentzian linewidth** can inferrred from the (E15) phase noise white noise floor:

$S_{white}(\nu=1\text{MHz}) < 1\ \text{Hz}/\sqrt{\text{Hz}}$ => $\Delta\nu_{Lorentzian} < 3$ Hz.



Coherence length and spectral linewidth

Spectral linewidth / coherence length is a key performance parameter for long range interferometric sensing (e.g. pipeline monitoring).

Spectral linewidth ~ coherence time:

$$\Delta\nu = 1/(\pi \cdot \tau_{coh})$$

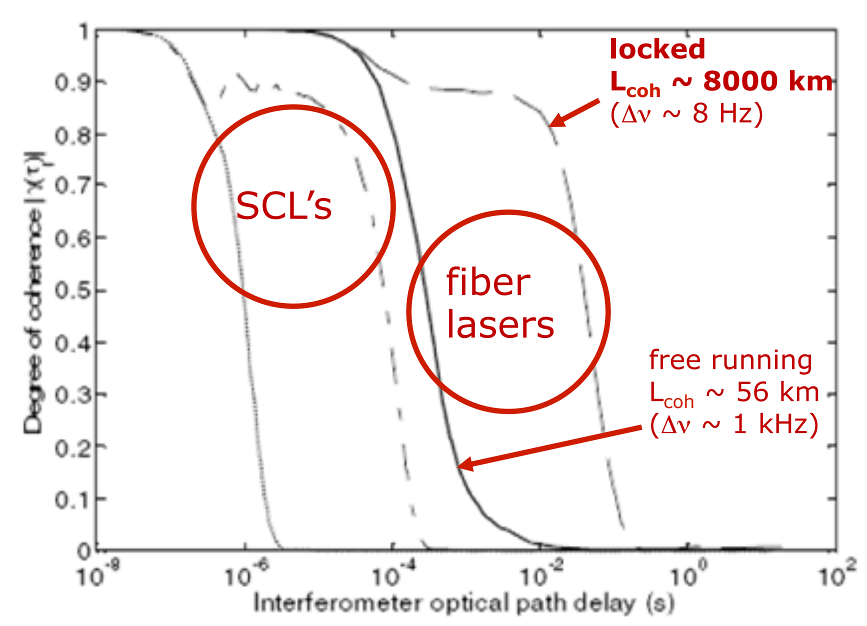
BUT this holds only for lasers with a *Lorentzian linewidth*.

Fiber lasers are typically limited by *Gaussian 1/f type noise*, and the spectral behavior is best viewed as a very narrow (sub-Hz) line subjected to frequency jitter over time.

The *measured* linewidth therefore represents the extent of the jitter over the integration time.

The real coherence length will typically be longer than what can be deduced from the inverse relation to the *measured* linewidth:

$$L_{coh} > c/(\pi \cdot n \cdot \Delta\nu)$$

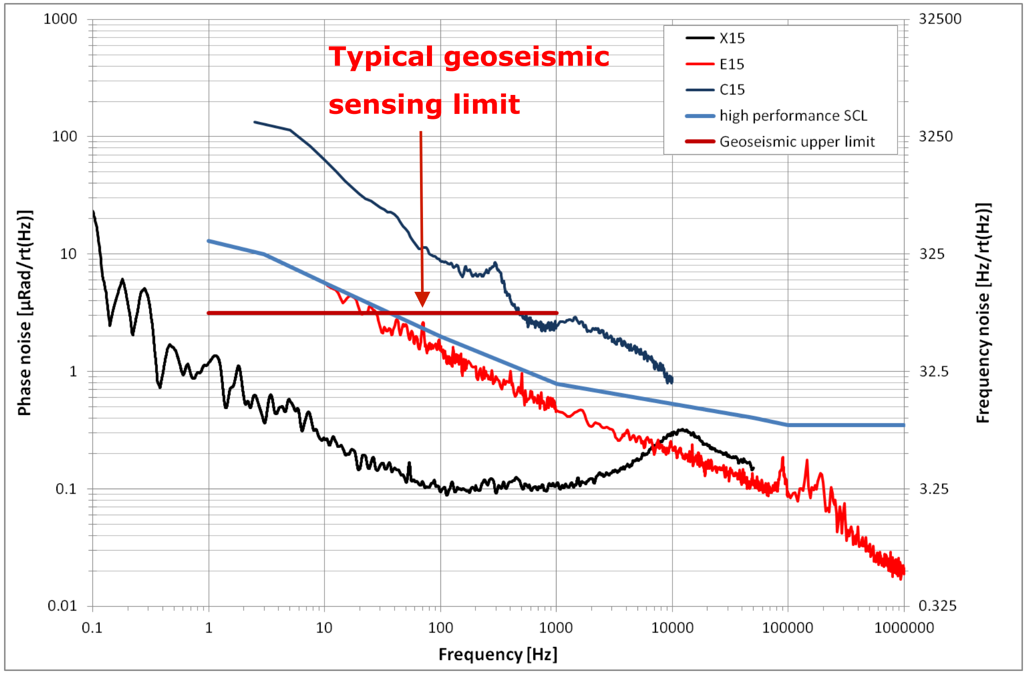


Phase / frequency noise

Combination of fiber waveguide properties, FBG cavity strength and long rare earth lifetimes account for a very low level of phase noise.

Phase noise at low frequencies (1 – 1000 Hz) is a key performance parameter for interferometric sensor lasers used in e.g. geoseismic applications.

Phase noise at high frequencies may affect system noise in the low frequency domain via aliasing – depending on the sensing scheme.

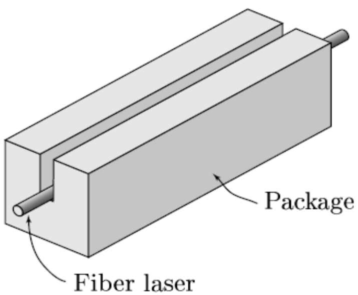


Fiber DFB laser frequency tuning

$\lambda_B = \Lambda_B(\varepsilon,T) \cdot n(\lambda_B,\varepsilon,T)$

Laser grating bonded to susbtrate =>

change wavelength by changing substrate length



Slow tuning - thermal tuning – mount fiber laser grating on e.g. aluminum substrate:

1. Fiber laser wavelength tunes as:

$$\frac{1}{\lambda} \bullet \frac{d\lambda}{dT} = \alpha_{substrate} + \frac{1}{n} \bullet \frac{\partial n}{\partial T} + \frac{1}{n} \bullet \frac{\partial n}{\partial \varepsilon} \bullet \alpha_{fiber}$$

2. **Thermal tuning range approx. 1 nm or 125 GHz** @ 1550nm

3. Slow tuning: approx. **1 GHz/sec**

4. Single mode operation maintained during tuning

Fast tuning - piezo frequency tuning

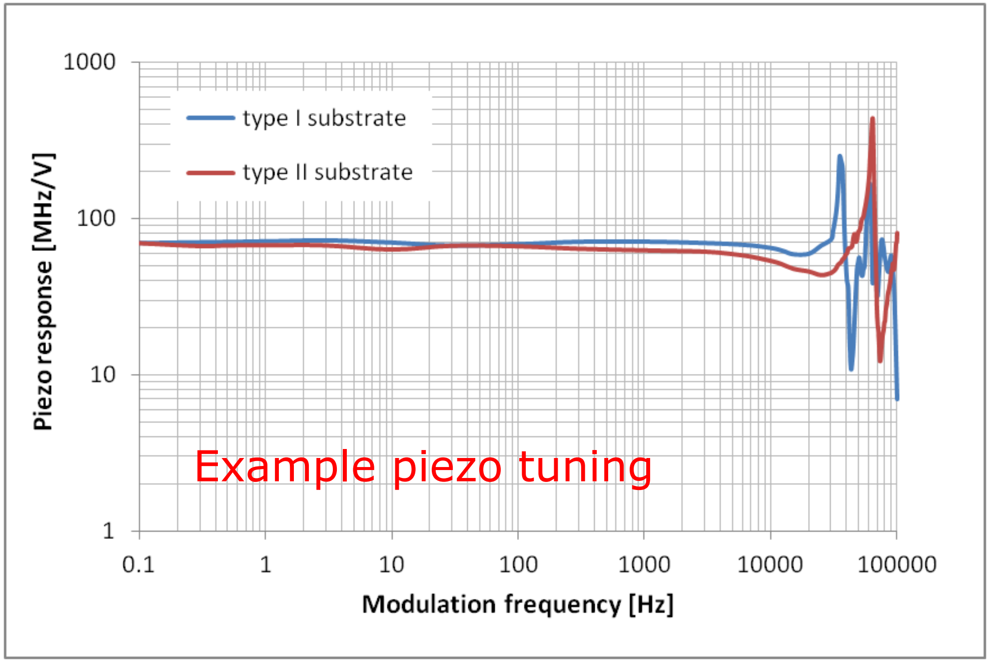
1. Piezo electric transducer built into substrate

2. Fiber laser wavelength tunes with Λ_B **(U_{piezo})**

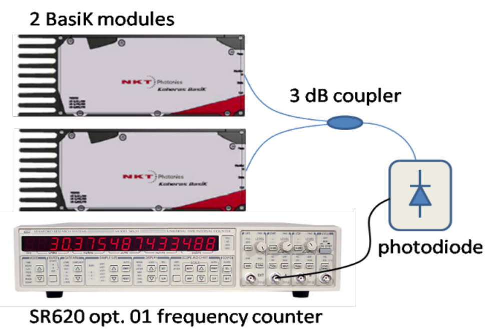
2.Tuning range. 25 - 500 pm or 3- 62 GHz @ 1550nm depending on piezo type

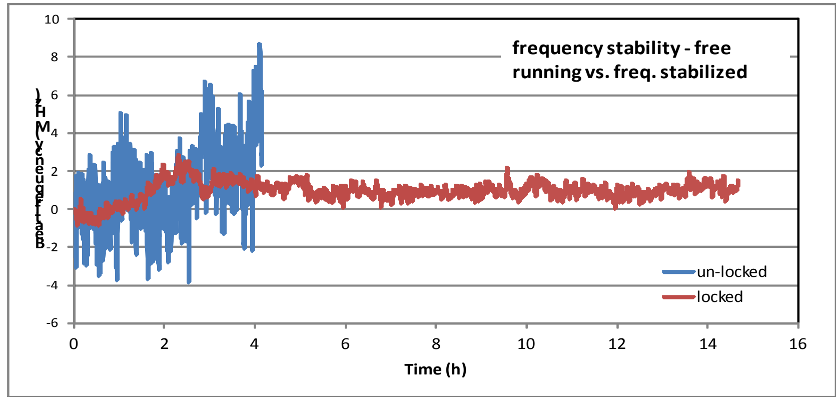
3.Tuning speed

4. Single mode operation maintained
   during tuning



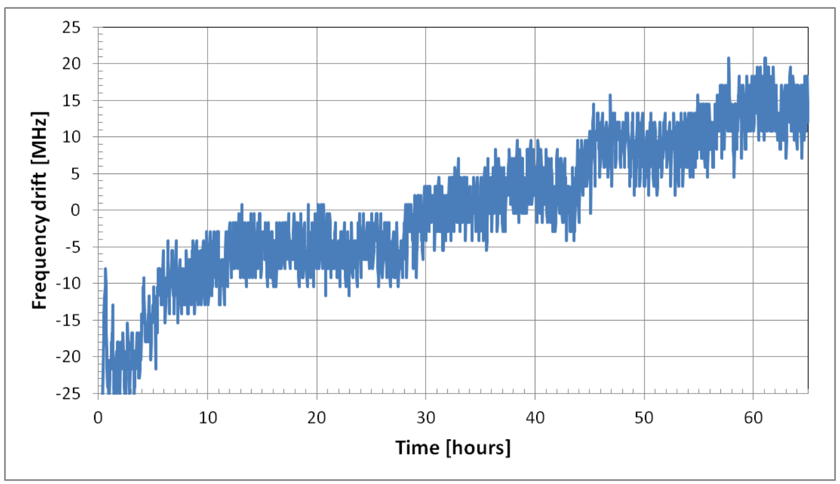
Frequency stability over time





Locked laser shows clear improvement in frequency stability over time:

frequency drift < 1 MHz/10 hours



Improved FL frequency stability:

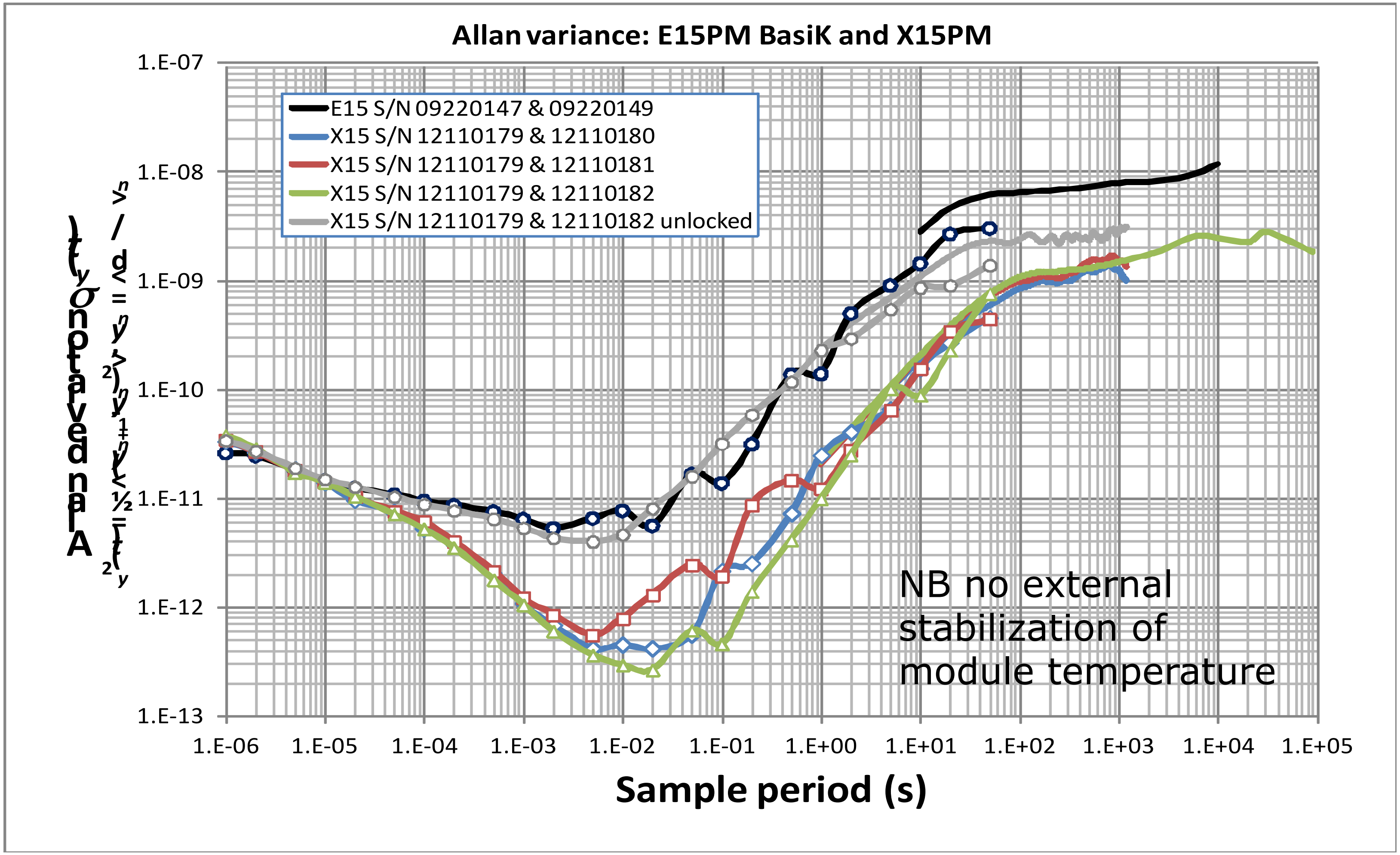
Single channel E15 long term stability measurement using high resolution wavemeter (Bristol 621A, 0.05 pm)

***Cold start**: datalog started 5 min after laser powered up*

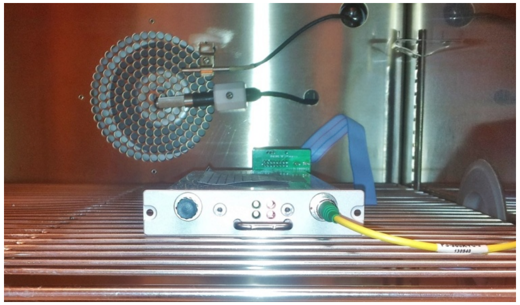
Total drift of < 50 MHz (0.3 pm) over > 60 hours

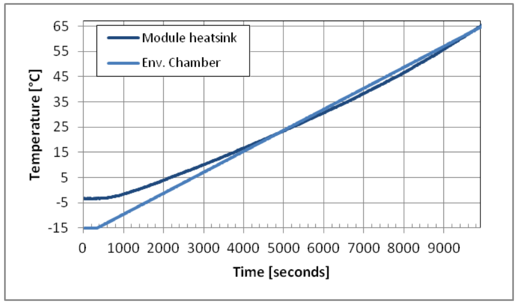
Good frequency stability useful e.g. for frequency conversion PDV experiments

Frequency stability – Allan Variance analysis



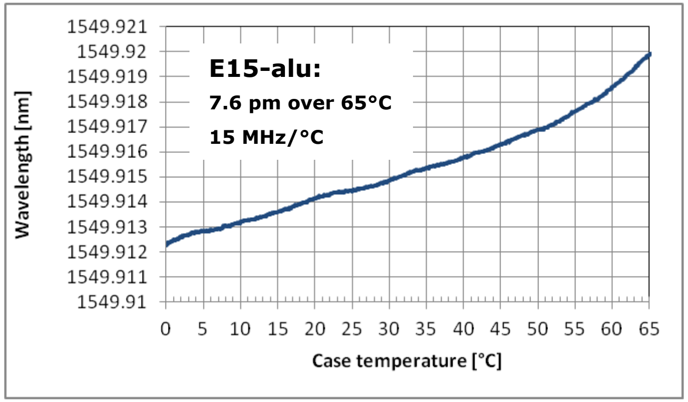
Frequency stability: ambient temperature



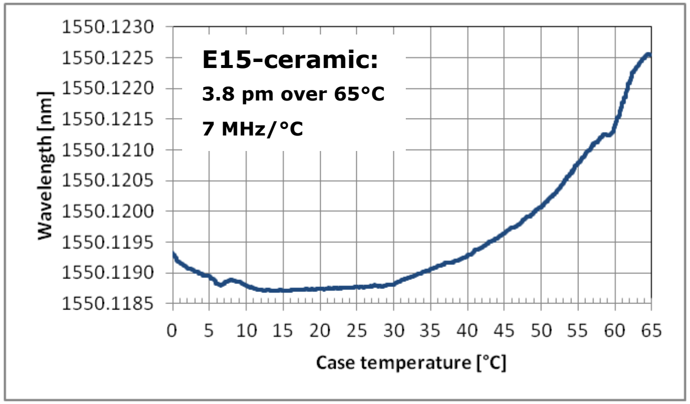


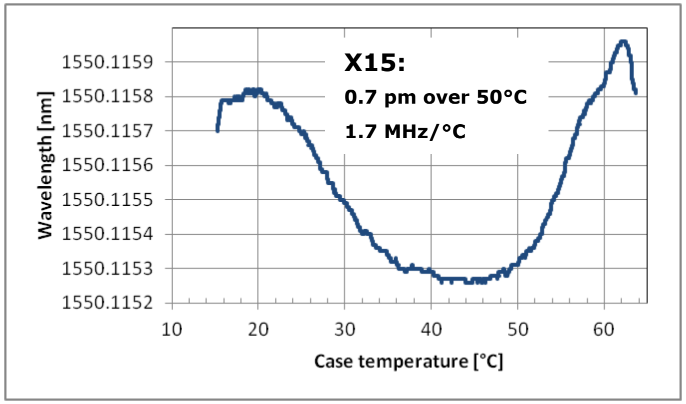
Temperature ramp: -15-70°C @ 0.5°C/min

Power consumption: 3 - 7 W @ 0-60°C case temperature



Frequency stable within a few pm over ambient temperature variations of up to 65°C



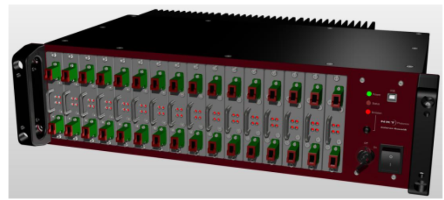


NKT Photonics
the power of light

Koheras Laser Solutions

10 W @ 1550

BoostiK System

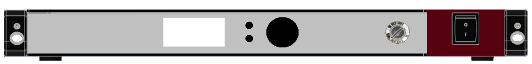


AcoustiK System
- **16 channels: 19” 3U**
- **32 channels: 19” 6U**

1 W @ 1550

BoostiK Module

Incremental Performance



AdjustiK System: 19” 1U
mW – 1 Watt

10 – 100 mW @ 1550

- Low to high power
- Single to multi wavelengths
- Laser properties are the same

AcoustiK system: multi-channel sources

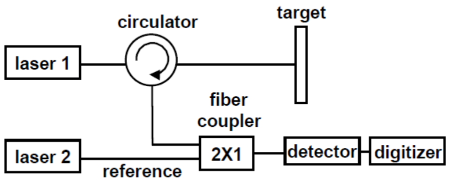
multiplexed system – single output fiber on back

multiplexed system - direct front panel access to individual laser modules

- **up to 32 channels - multiplexed & direct front panel access versions**
- **16 channels 19” 3U, 32 channels 19” 6U**
- **Passive cooling**
- **90 – 264 AC supply**

Applications:

- DWDM interferometer interrogation (e.g. geoseismic sensor systems)
- frequency conversion PDV...



.... Tune wavelengths to get any desired beat frequency, Dolan, 2010

High power sources

BoostiK System:

- up to **10W @ 1550nm**
- possibility for built-in **power splitting**, e.g. 1x8 with 8 SM output fibers, P > 1 Watt per fiber
- applications:
  - scientific
  - PDV including many-point PDV

High power sources

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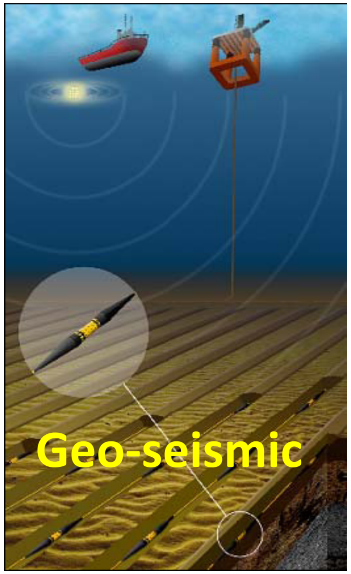
Application examples



Photos placed in horizontal position
with even amount of white space
between photos and header

PDV with NKT Photonics 10W laser

With integrated 1x8 splitter

courtesy of Brook Jilek, Sandia National Labs

SAND 2014-4729P for Unclassified Unlimited Release

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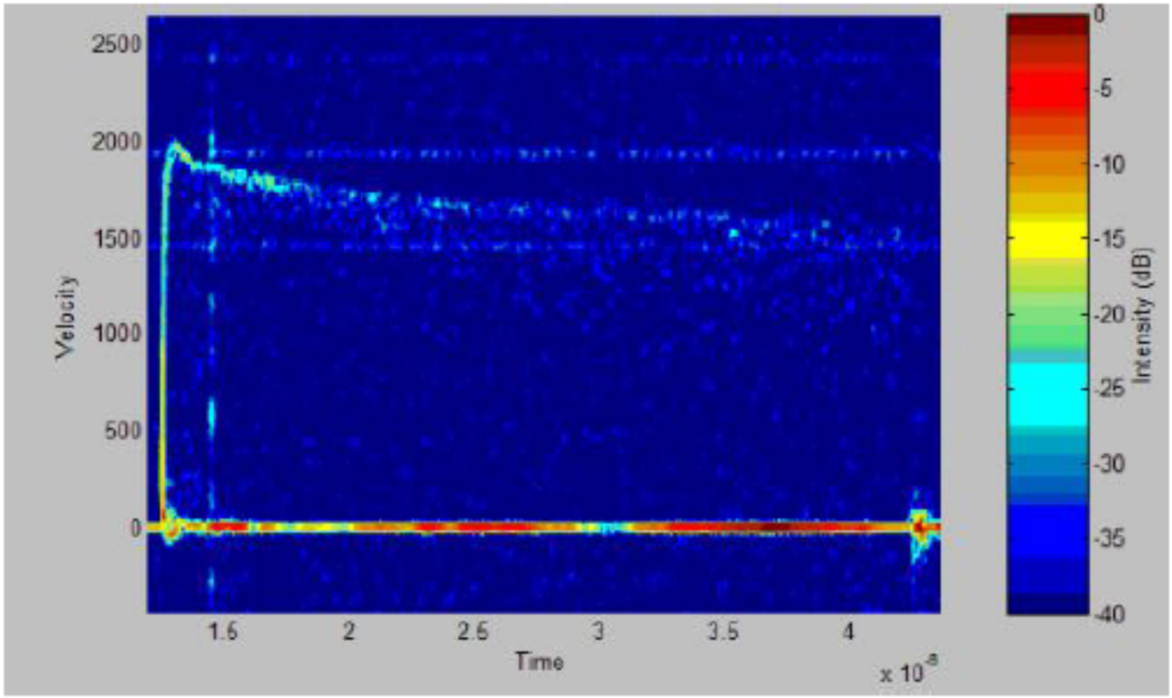
PDV on laser-driven flyers

- Aluminum flyers ~ 300 μm diameter
- Collimating probe
- Impact into window 6 mm away
- 1W power through probe onto target
- Flyer breaks up, but fragments are tracked until impact with window 3 μs later
- Data courtesy of Brook Jilek (Sandia National Labs)

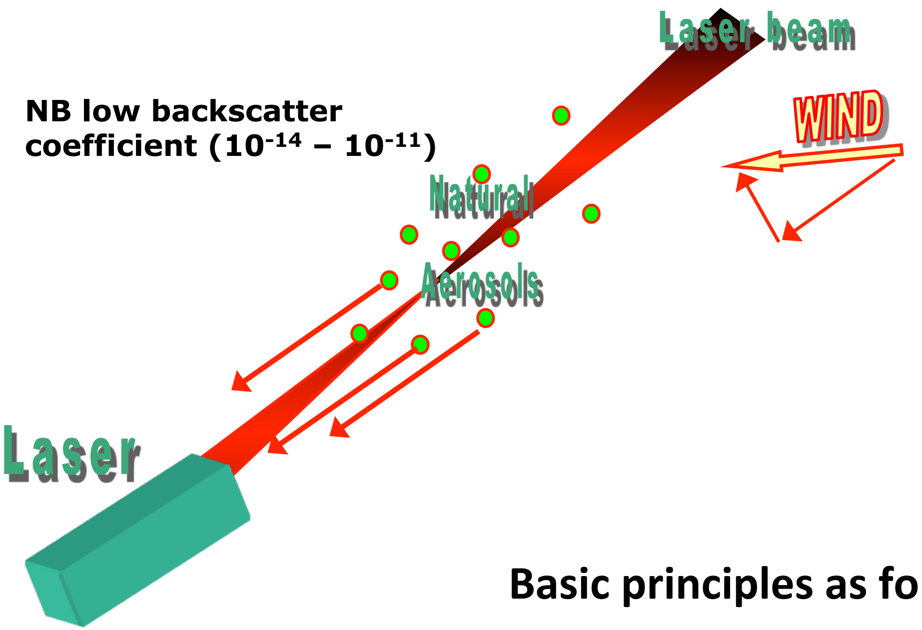


This experiment used one of the eight fibers, P ~ 1 Watt (i.e *not* a many-point PDV setup – although source prepared for this)

Wind LIDAR - Energy

- Site surveying for wind turbine farms
- Wind turbine control
- Improve safety & lifetime
- Optimize power efficiency
- Lower TCO

LIDAR for wind speed measurements



NB low backscatter coefficient (10^{-14} – 10^{-11})

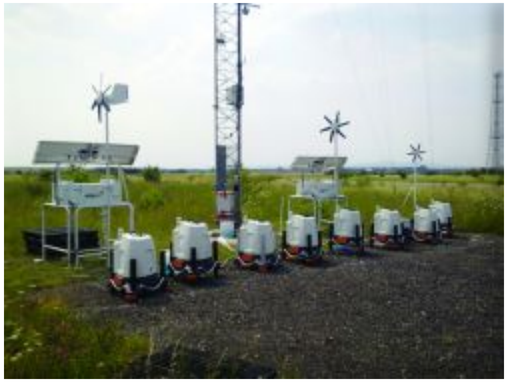
Detection: coherent mixing of back-scatter with LO.

Doppler shift provides radial wind speed.

Basic principles as for PDV, but with two major differences:

- scattering off atmospheric aerosols => back scatter coefficient many orders of magnitudes lower than in PDV (hard target). This puts stringent **demands on laser noise (linewidth, RIN) and power** to compensate for the weak back scatter signal.
- wind speed region of interest: few m/s up to 50 m/s. This **limits the receiver bandwidth requirements to some 10's of MHz.**

LIDAR - wind



Courtesy of Zephir, UK

Geo-seismic sensing for Oil & Gas

Geoseismic sensing: airgun + hydrophone array.

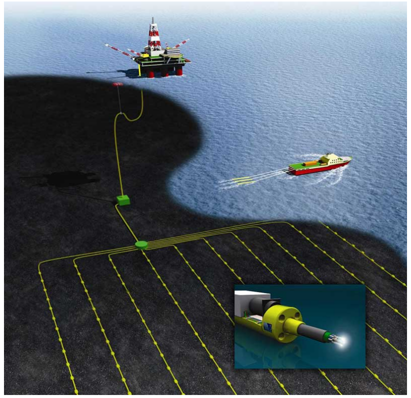
- Systems have traditionally been based on electric transducers (e.g. piezo electric hydrophones)
- new systems based on fibre optical sensors are now available

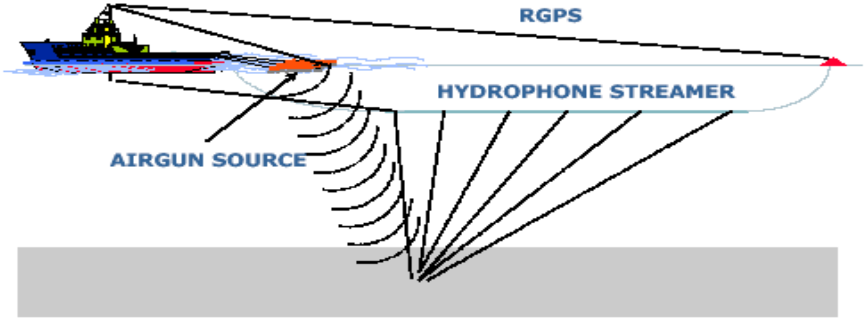
Search for new oilfields (streamers)

Permanent reservoir monitoring:

- Today typically only 30% of a well is exploited.
- Improved Oil Recovery: permanent monitoring systems may increase the utilisation

Hydrophones consist of fiber optic interferometers that are sensitive to acoustic pressure. DWDM network of interferometers perform 'tomography' on geological structures below seabed. Sensitivity requirements for the entire system puts a very stringent demand on **low laser phase noise**.





Summary

The Koheras BasiK DFB Fiber Laser is a perfect match for fiber optic sensing applications – including PDV:

- compact, fiber coupled laser source
- single mode – also during frequency tuning
- low phase noise & narrow linewidth ~ long coherence length
- high frequency stability over time and under changing ambient temperature
- fast & wide range frequency tuning - 10's of GHz tuning @ kHz speed
- high power (up to 10 W @ 1550nm) – with possibility for power split (e.g. 1x8)
- multi-wavelength systems
- remote digital control